Low Power Carbon Nanotube Chemical Sensor System

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**CICC
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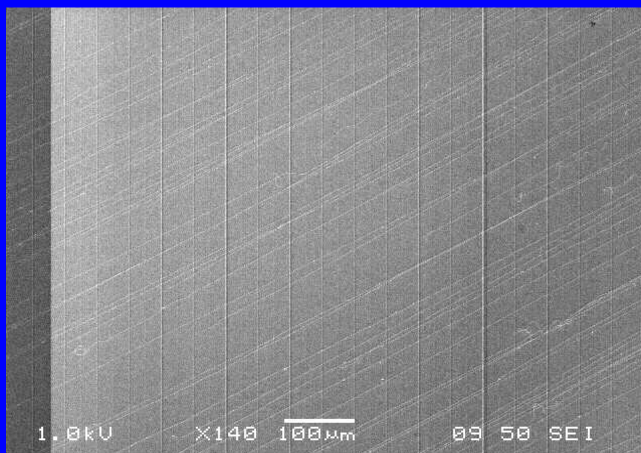
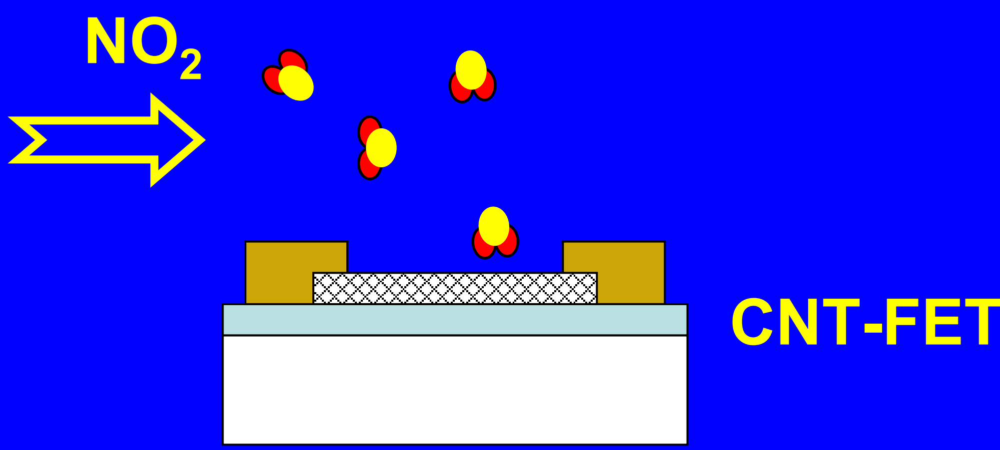
Outline

- Introduction
- Carbon nanotube chemical sensors
- Sensor interface design
- Interface chip measurement
- Chemical sensor system test result
- Conclusion

Motivation for using CNT Sensors



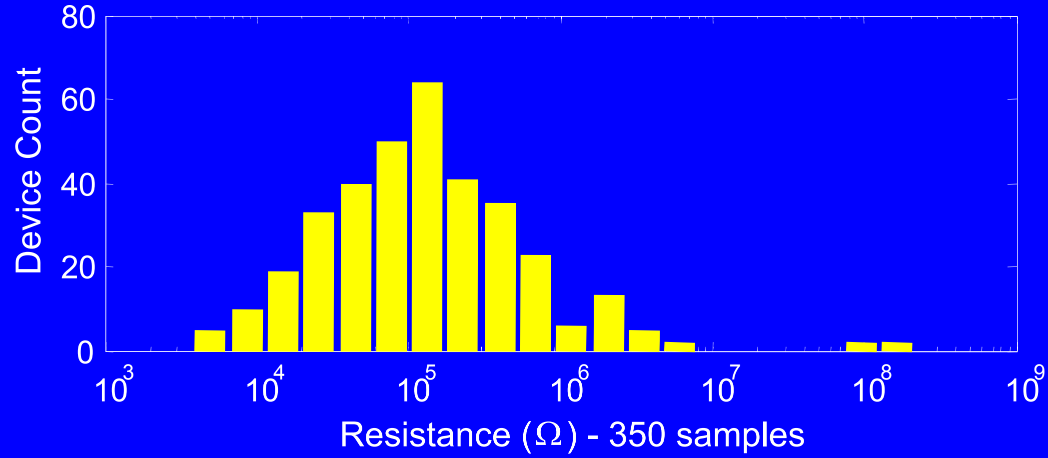
[Courtesy: A. Recco, J. Kong]



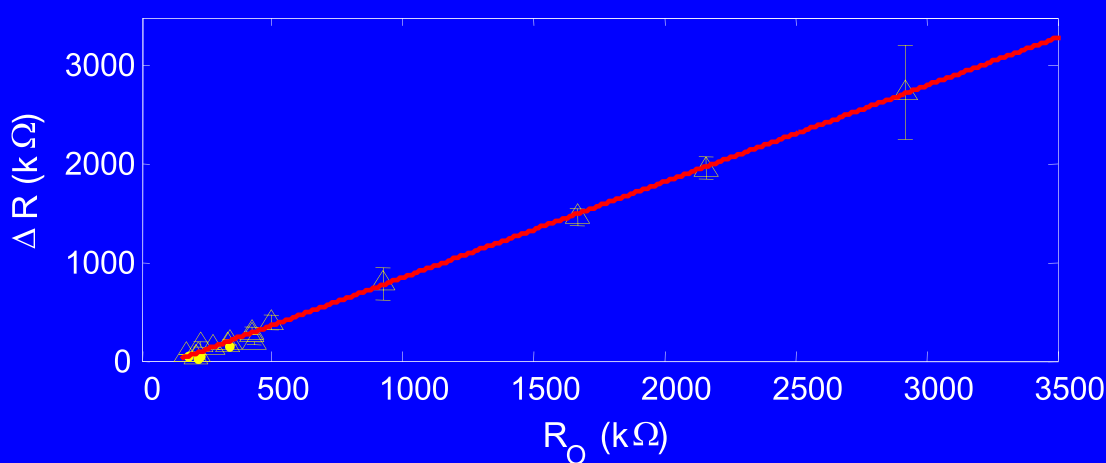
- Behaves as a resistive chemical sensor
- High sensitivity at room temperature
  - No need for micro hot-plates
- NO_2 can be sensed without any functionalization

Measured CNT Characteristics

R_{CNT} Distribution



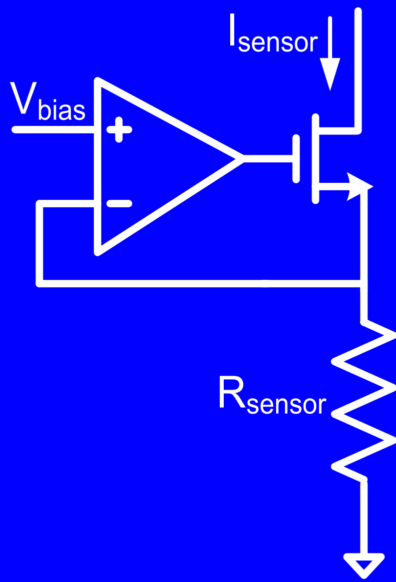
Δ R vs. R_O (300ppm NO_2)



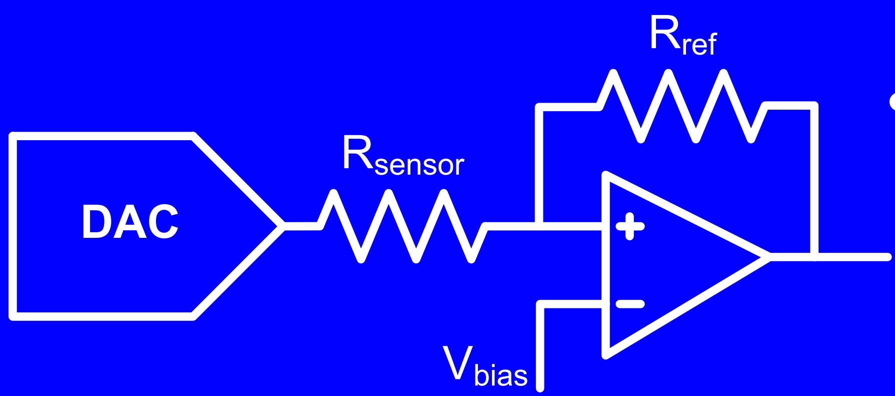
Implications for the CMOS backend

- Wide dynamic range (10kΩ ~ 9MΩ), but only moderate resolution (1%)
  - Sub-ppm NO_2 detection
  - 16 bit dynamic range
  - 6-7 bit resolution
- Interface to multiple CNT sensors for increased reliability
  - Access to 24 CNTs
- Maximum current through a single CNT < 30 μA

Previous Sensor Interfaces



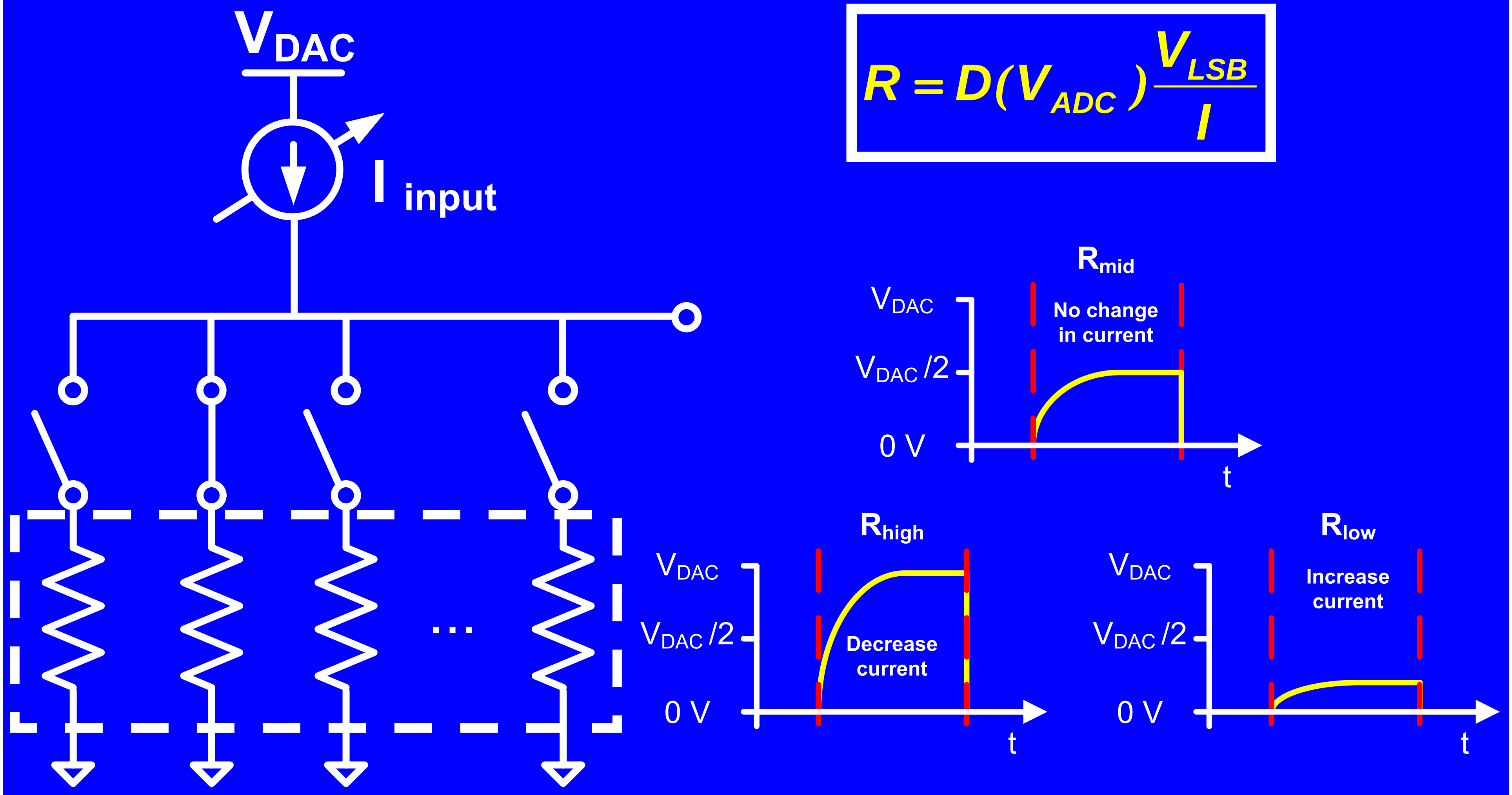
- Make resistive sensor a current source by wrapping an OPAMP to supply a constant voltage across the sensor [Malfatti et al. ISSCC06]



- Use a resistive DAC and ADC to gain a wide dynamic range [Grassi et al. ESSCIRC 2005]

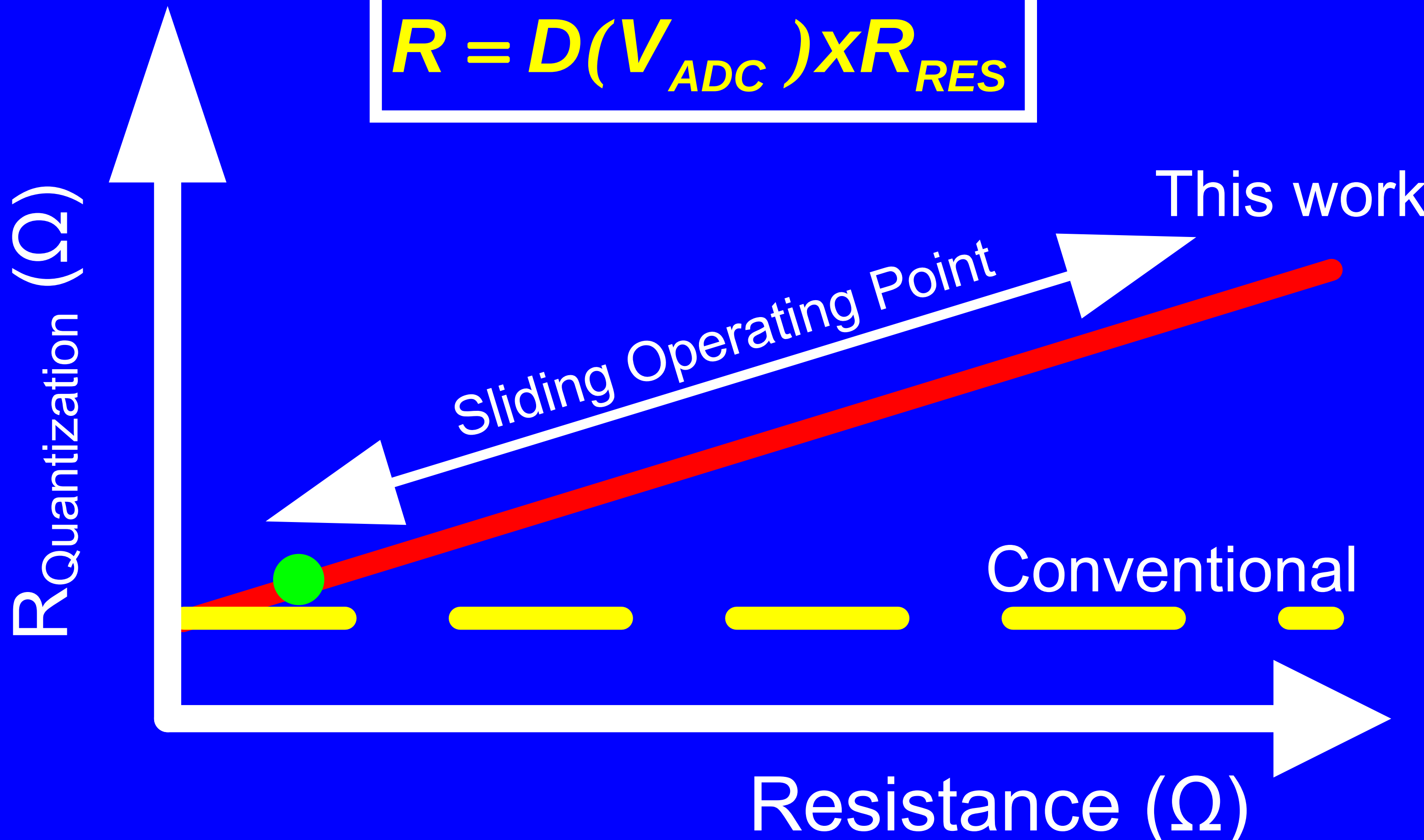
Architectural Concept

$$R = D(V_{ADC})\frac{V_{LSB}}{I}$$



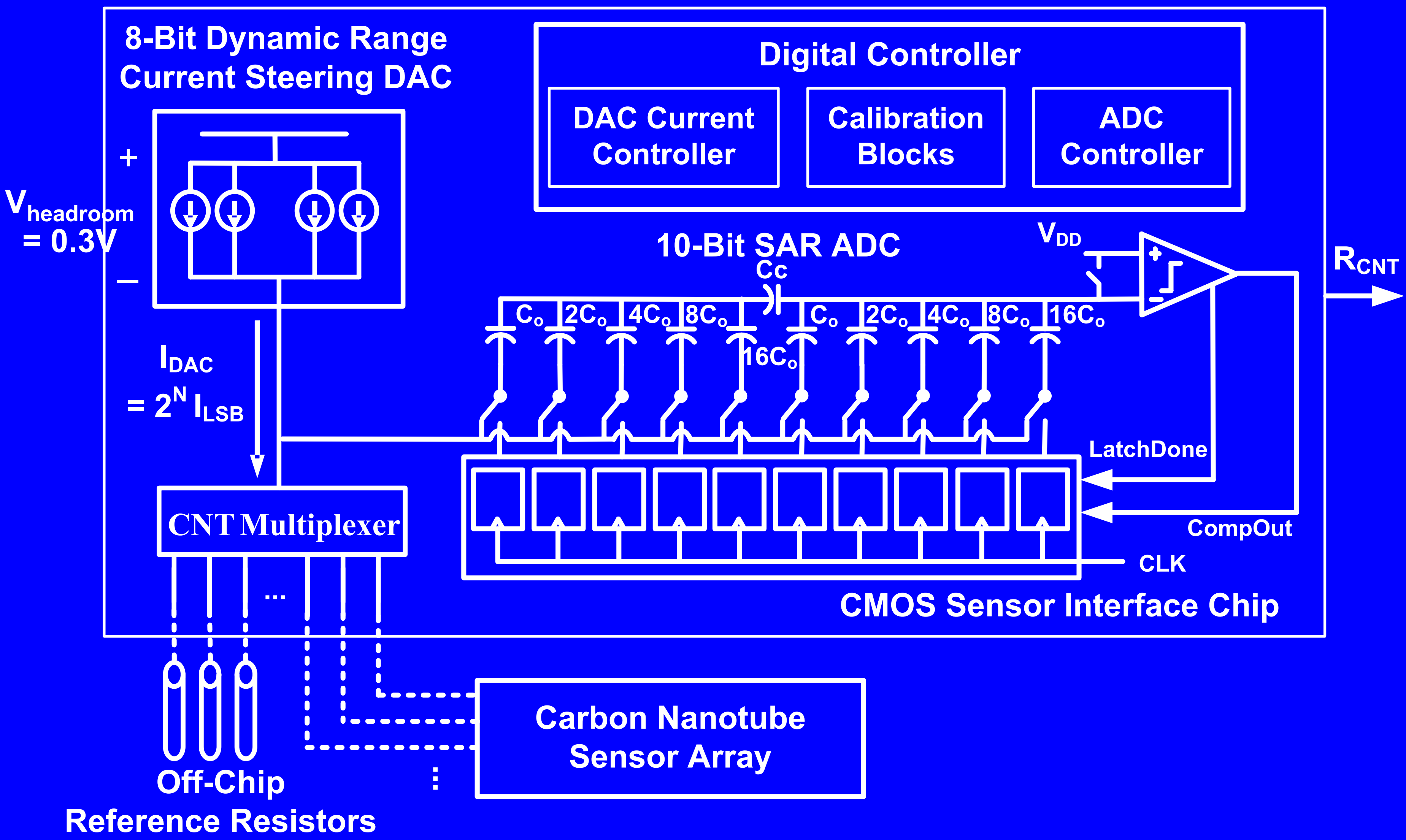
Architectural Concept

$$R = D(V_{ADC})xR_{RES}$$



No need for 16-bit ADC, but can let the adaptive controller determine the operating point of the interface

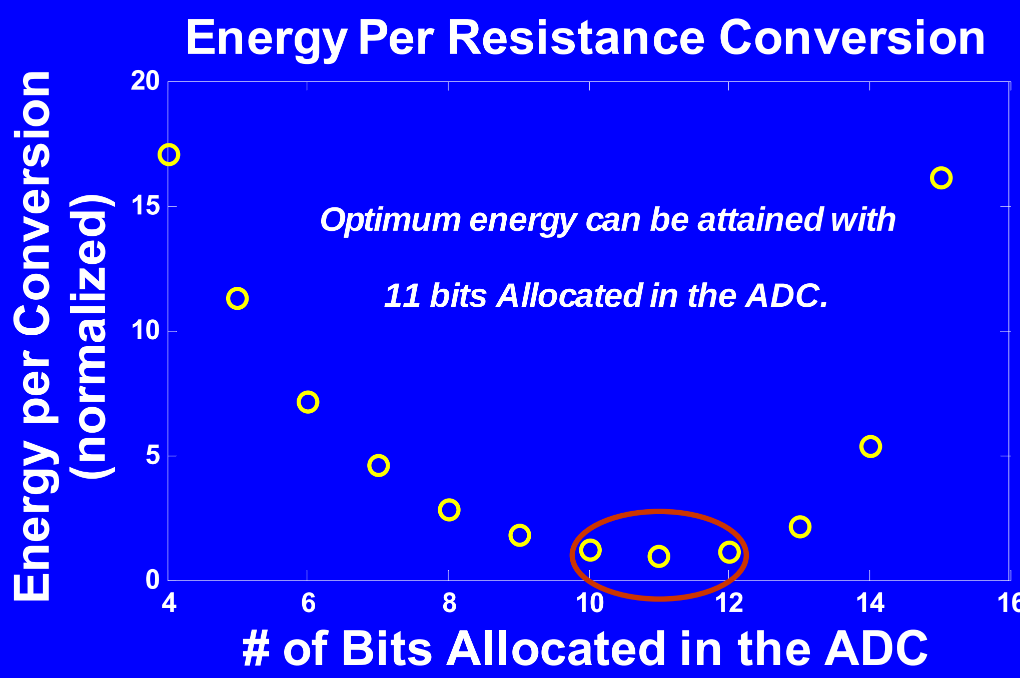
Proposed System Diagram



Architecture Optimization

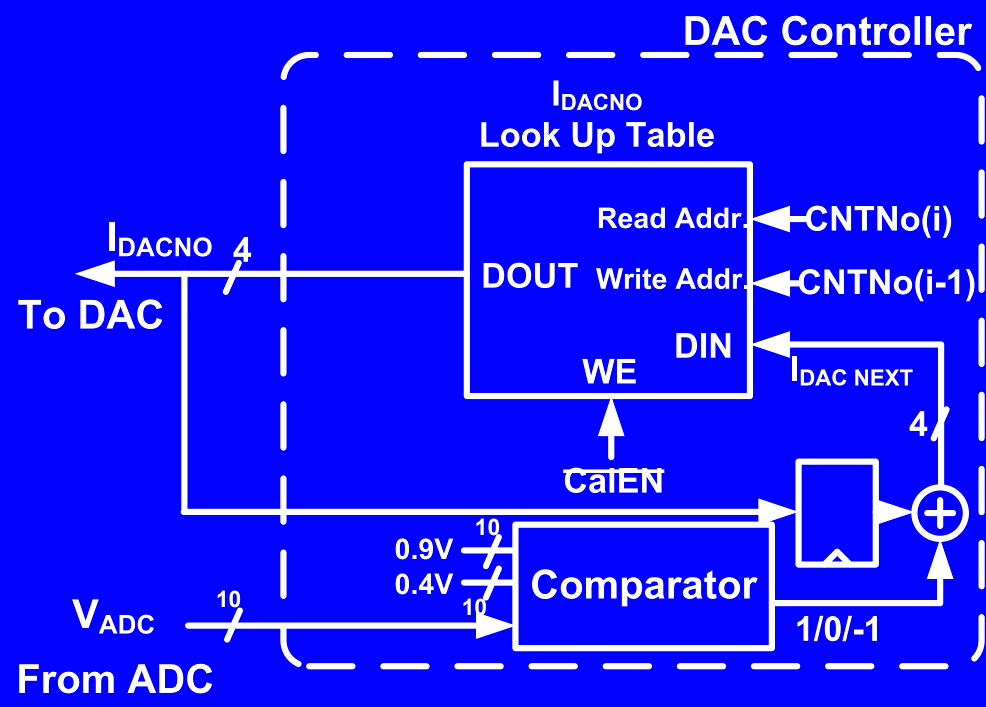
Why a 10-bit ADC and a 8-bit DAC to attain 18-bit dynamic range?

$$E_{SYSTEM} = P_{ADC}T_{ADC} + P_{DAC}T_{DAC} + E_{DIGITAL}$$



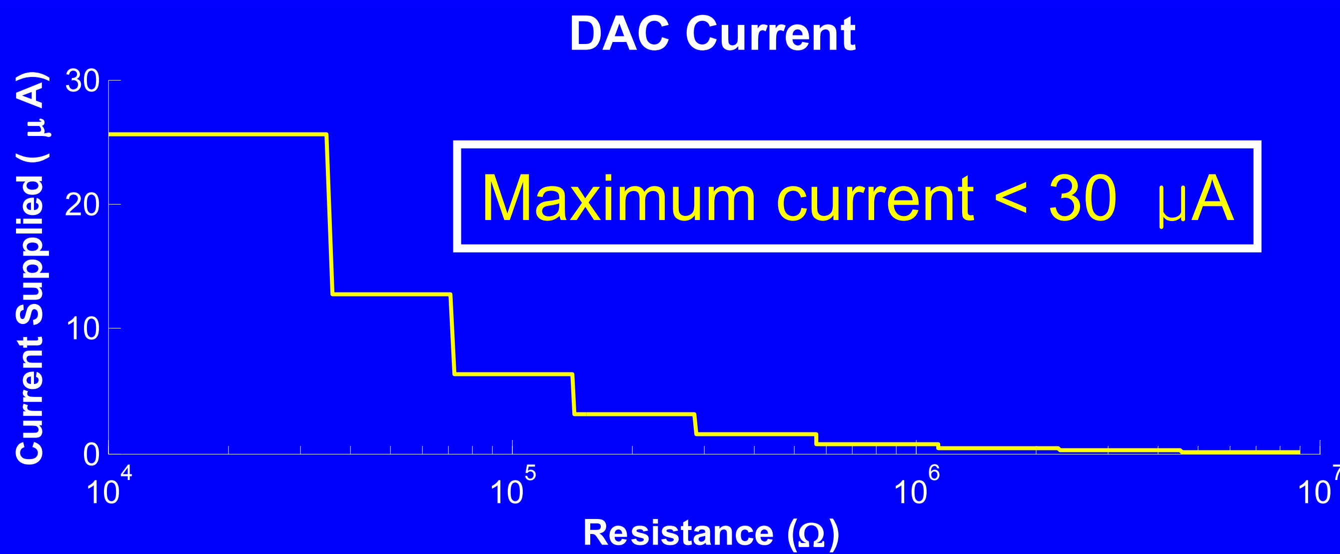
Penalty paid for using a 10-bit ADC is 17%

DAC Control Scheme

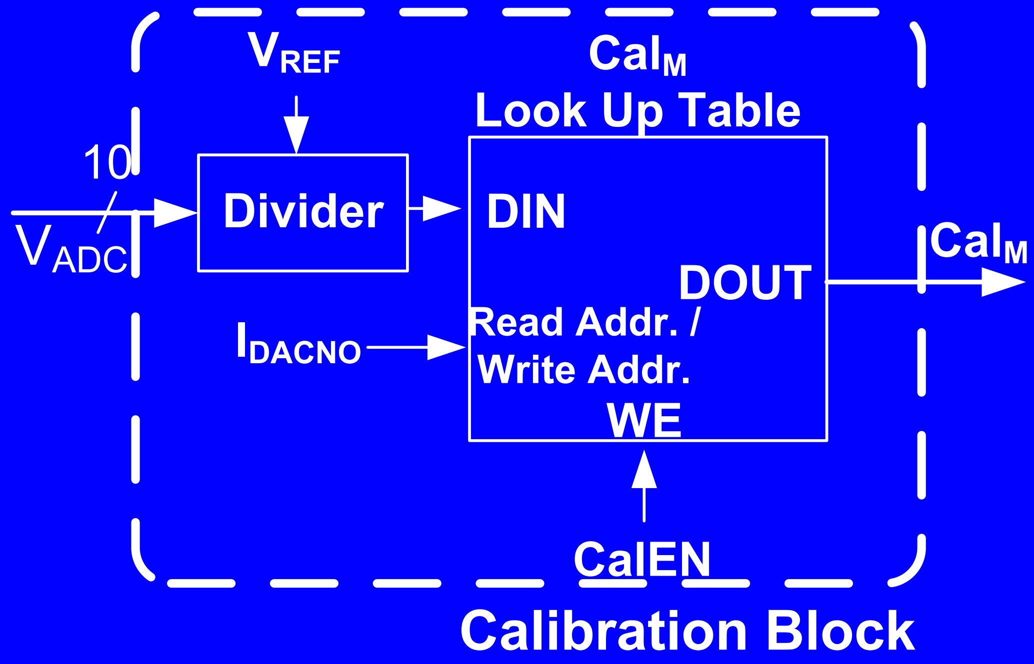


- Only allow $I_{DAC} = 2^N I_{LSB}$: 4-bit representation of current.
- Supply the maximum current while meeting the DAC headroom constraint.
- Resistance can be calculated with register shift operations

DAC Control Scheme

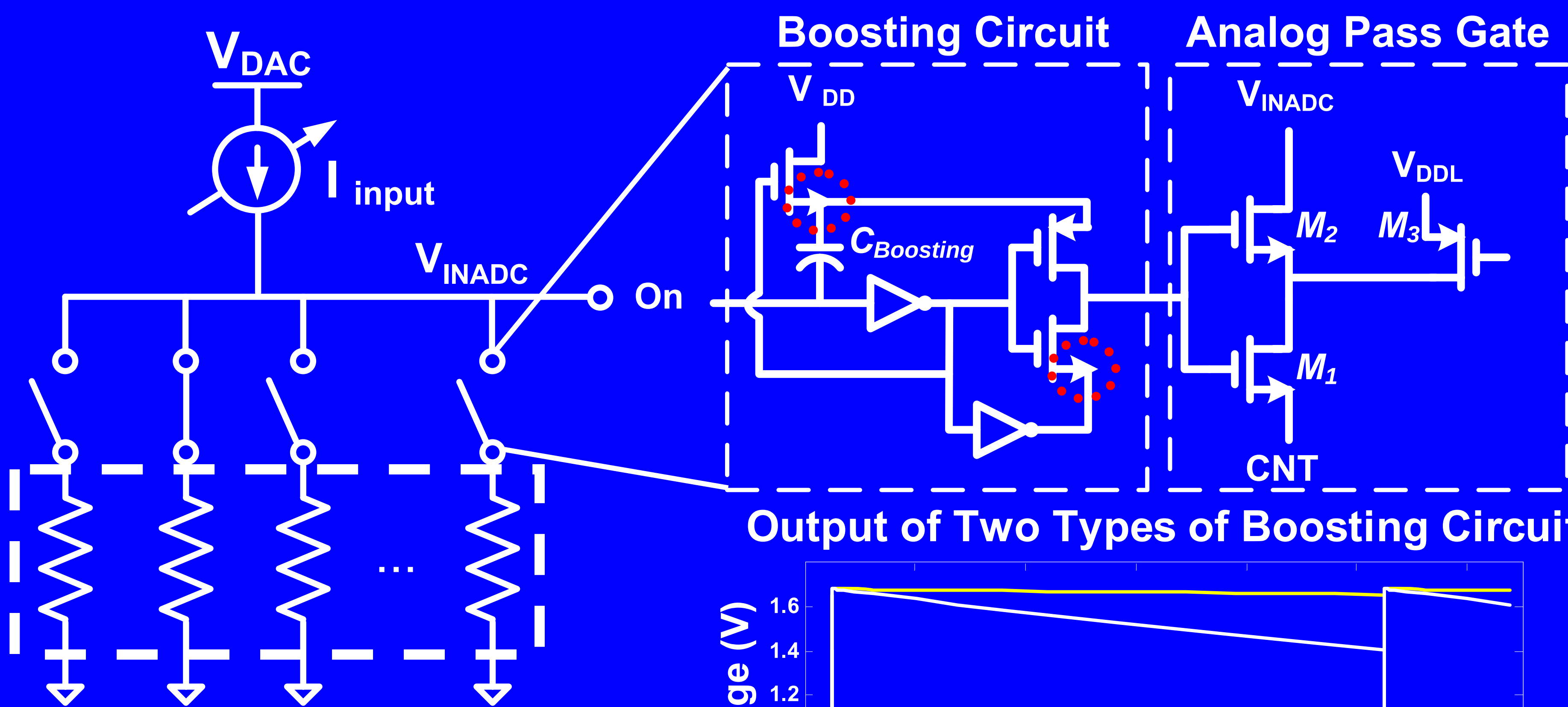


DAC Calibration



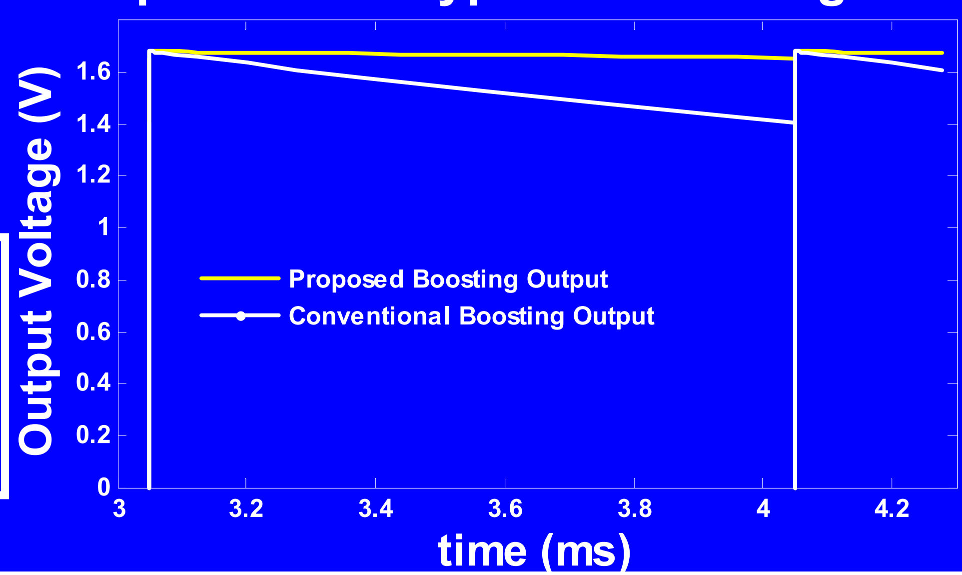
- Use off-chip reference resistors to measure how much current is being sourced at each current level
- A simple multiplication can be used to calibrate the DAC nonlinearity

Analog CNT Multiplexer



The width of pass gate transistors are made reasonably large, and the voltage is boosted when turned on, to reduce the on-resistance

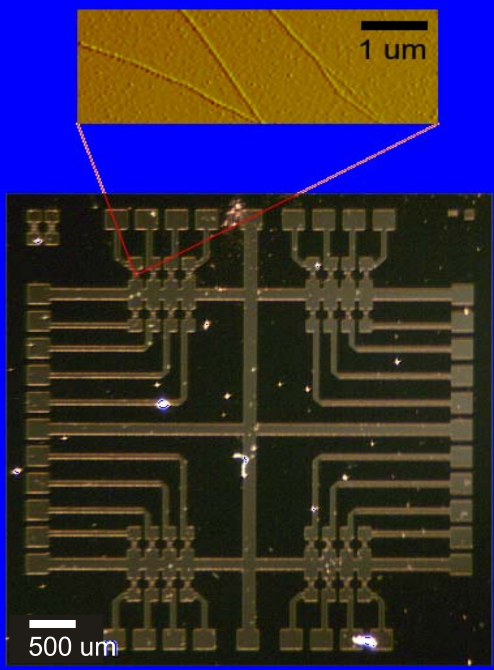
Output of Two Types of Boosting Circuit

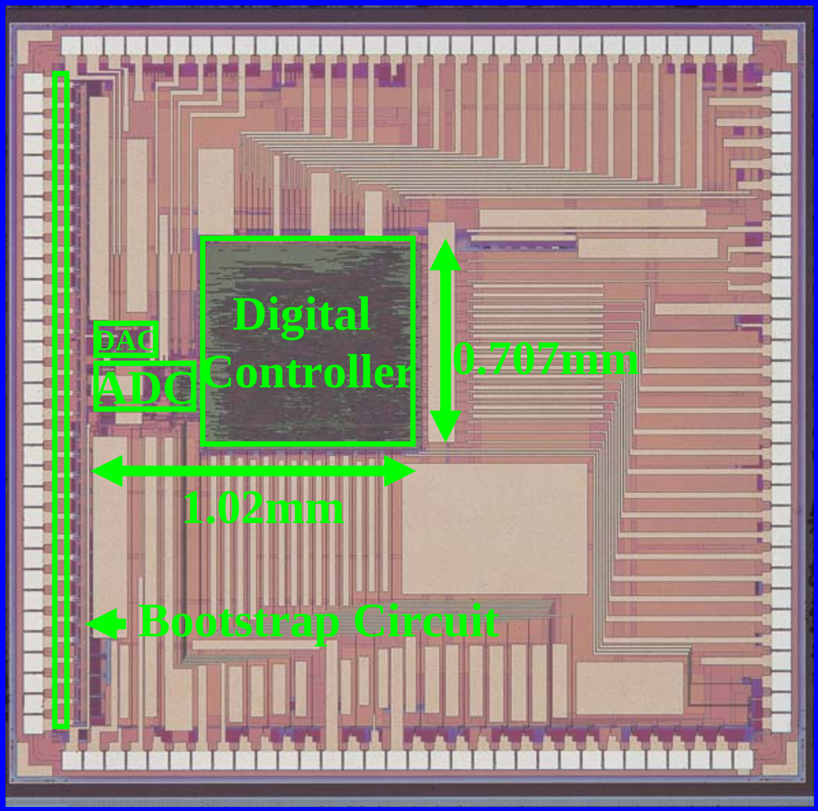


Prototype Chips

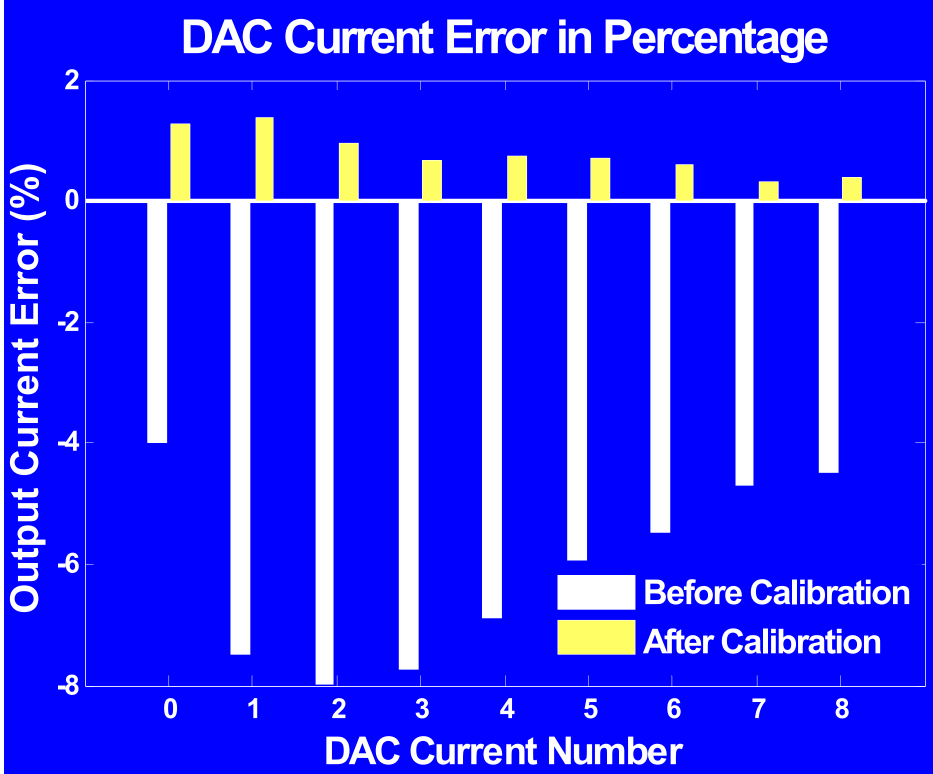
CNT sensors fabricated at MTL, RLE (MIT)

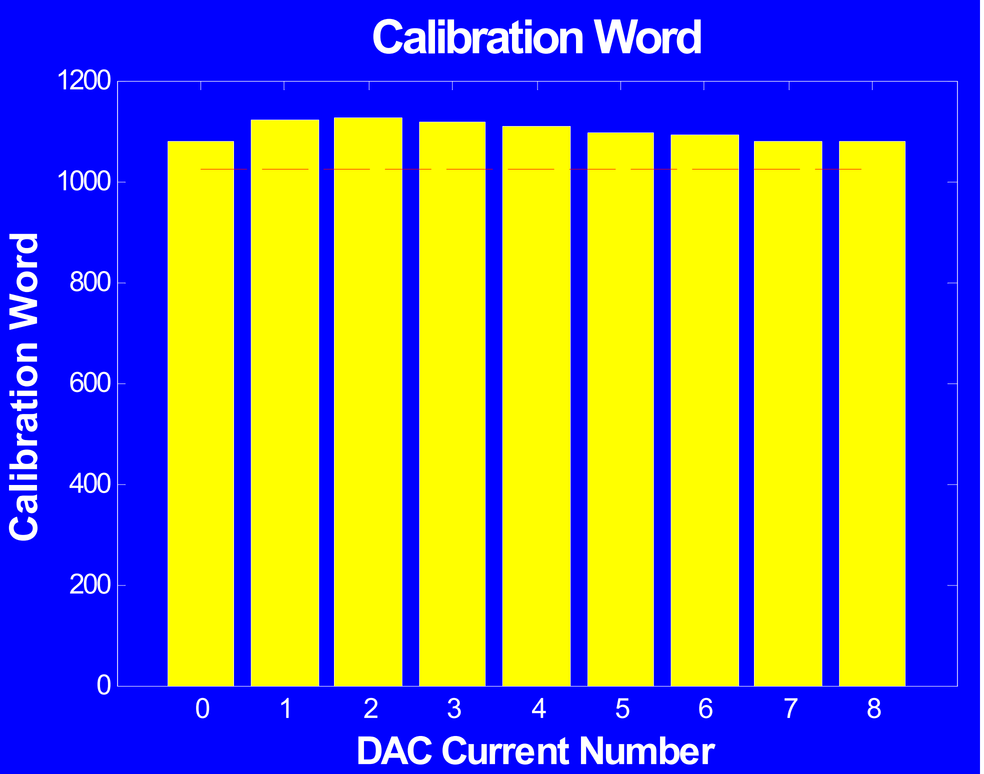
Prototype fabricated in 0.18μm CMOS process





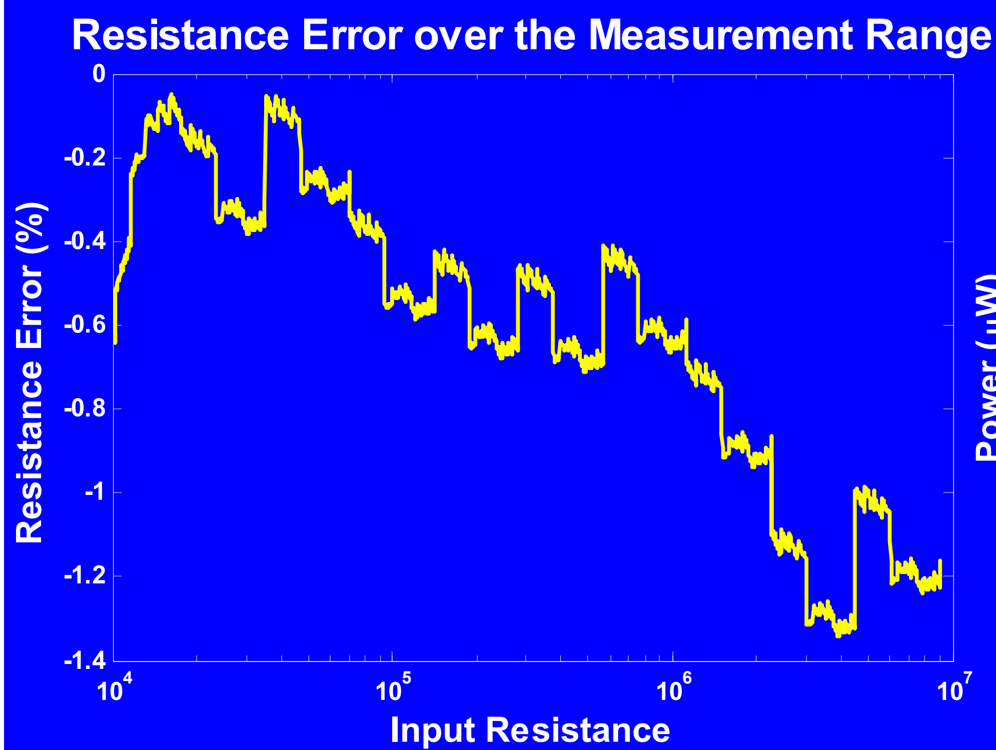
Performance : DAC Calibration

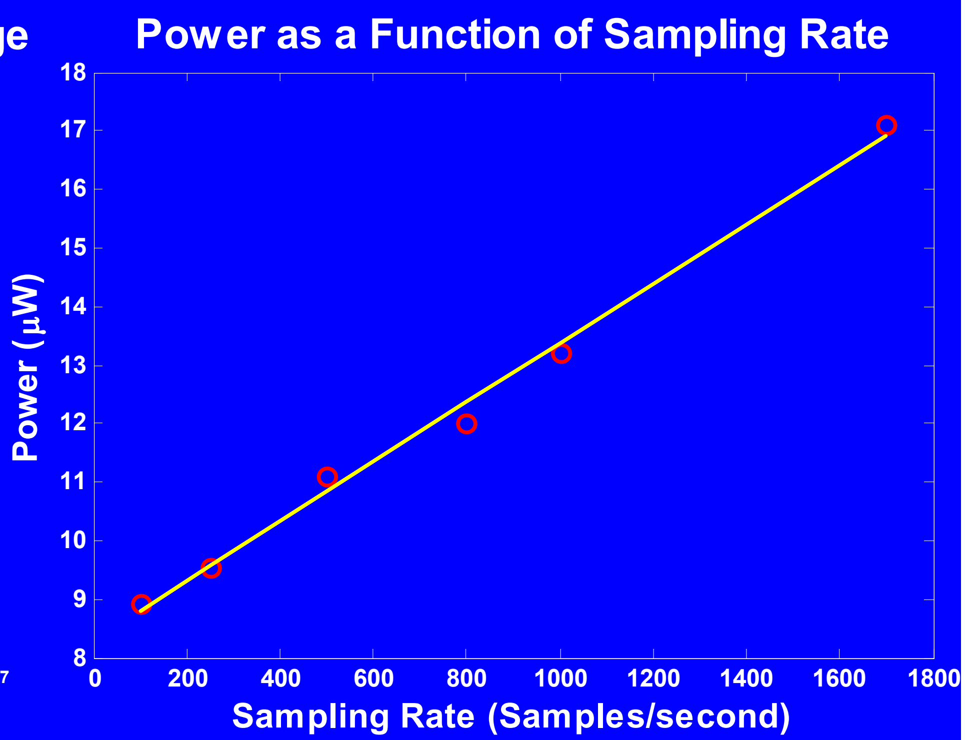




Current linearity error is kept below 1.2% after calibration

Performance : Linearity and Power





Measurement error is kept below 1.34% across the whole dynamic range

Linear power scaling as sampling rate is reduced

Worst case power: 32 μW

Comparison of interfaces

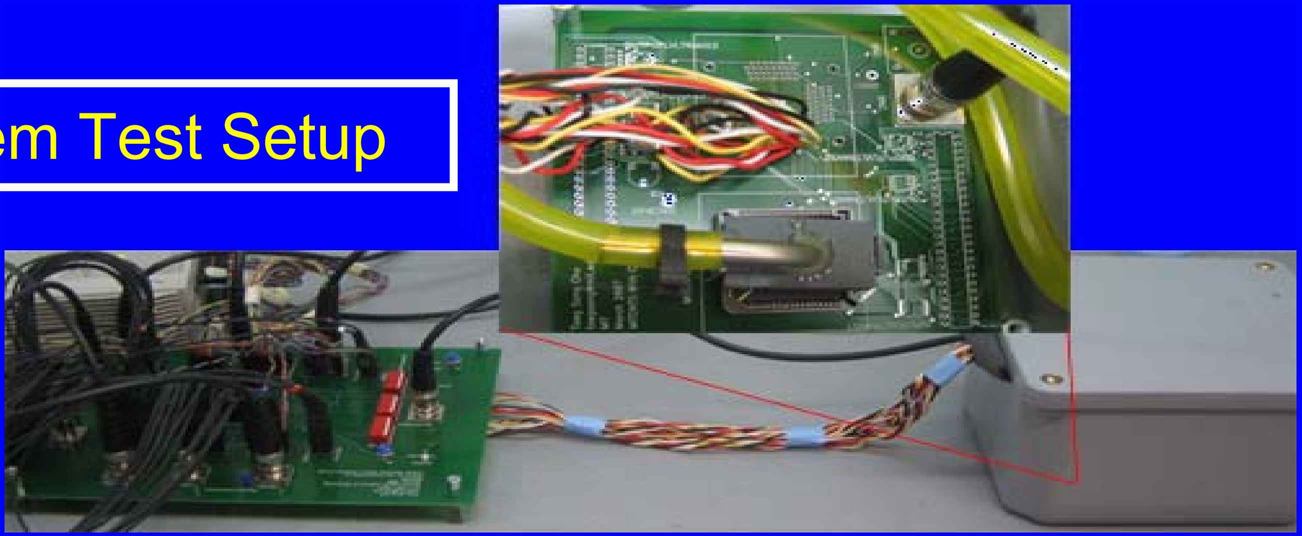
	Readout Resolution	Resistance Range	Readout Rate	Power Consumption[η]
Malfatti et al. [ISSCC06]	0.5% >	500kΩ ~ 1GΩ	Not Available	3.1 mW
Grassi et al. [ESSCIRC05]	0.14% >	100Ω ~ 20MΩ	100Hz	6 mW
Frey et al [JSSC 07]	0.2% >	3kΩ ~ 12MΩ	3kHz	~ 130mW
Flammini[*]	0.5 % >	10kΩ ~ 10GΩ	Depends on resis.	600 mW
This work	**1.32% >**	**10kΩ ~ 9MΩ**	**1.83kHz**	**32 μW**

* IEEE Transactions on Instrumentation and Measurement Nov 2004

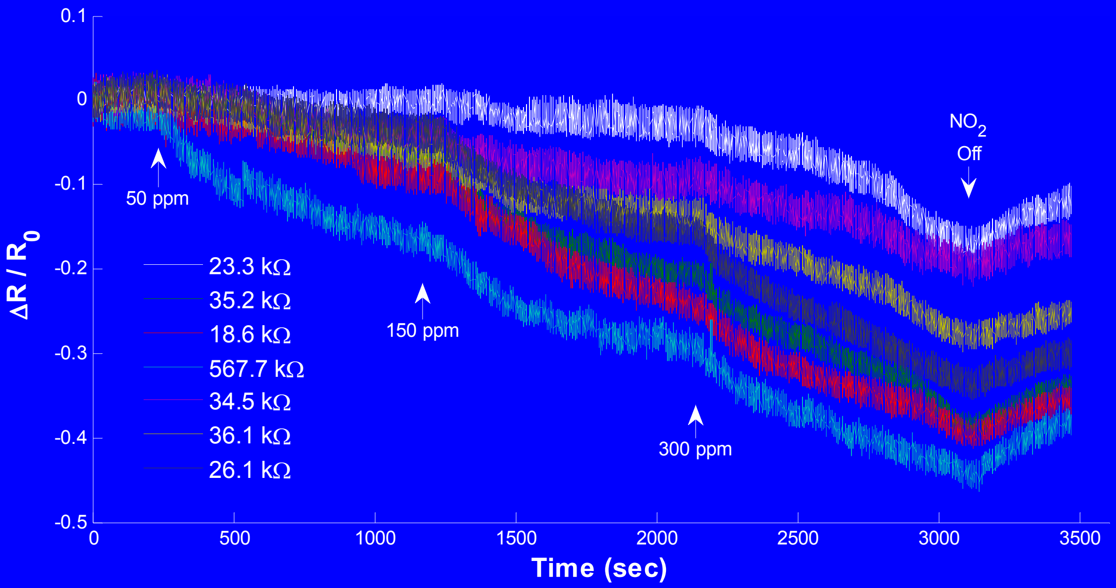
η Excluding micro-hotplate power where applicable

Chemical System Testing

Chemical System Test Setup



A resistance change in CNT due to chemicals is reliably measured



Conclusion

- CNT sensors enable a low power chemical sensor system without micro hotplates
- The designed interface chip attains a wide dynamic range by automatic control scheme
- The full chemical sensor system is demonstrated

Acknowledgements: Funding provided by MARCO IFC, Samsung Scholarship Foundation, Intel; Chip fabrication provided by National Semiconductor